Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 1 (2009) 2251–2259
Energy Procedia
www.elsevier.com/locate/procedia

GHGT-9

Monitoring at the CO_2SINK Site: A Concept Integrating Geophysics, Geochemistry and Microbiology

R. Giese[a], J. Henninges[a], S. Lüth*[a], D. Morozova[a], C. Schmidt-Hattenberger[a], H. Würdemann[a], M. Zimmer[a], C. Cosma[b], C. Juhlin[c], and CO2SINK Group

[a]GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
[b]Vibrometric Oy, Jaakonkatu 2, 01620 Vantaa, Finland
[c]Uppsala University, Villavägen 16, 752 36 Uppsala, Sweden

Abstract

At the CO2SINK site (Ketzin, near Berlin, Germany), the pilot study for onshore CO2 storage in saline aquifers includes monitoring of the storage reservoir and the structures above using physical, chemical, and microbial observations. Seismic and geoelectric measurements have delivered the structural framework and monitor CO2 propagation between two observation wells. Borehole temperature data serves to derive information about in-situ formation temperatures and to detect processes related to the injection and movement of CO2 in the subsurface. Pressure measurements aim at ensuring safe operations and characterization of the reservoir. For a complete characterization of the CO2 storage process, the physical observations have to be complemented by chemical and biological probing, as fluid/fluid and fluid/rock interactions and microbial processes play an important role possibly affecting the stability of the reservoir and caprock. A newly developed Gas Membrane Sensor detected the CO2 breakthrough on the first monitoring well. Microbial investigations contributed in optimizing the injection borehole after recognizing organisms reducing its injectivity.

reservoir monitoring; seismics; electrical resistivity; P-T; chemical sensor; microbial probing.

1. Introduction

The CO_2SINK project at the German town of Ketzin (near Berlin), is aimed at a pilot storage of CO_2, and at developing and testing efficient integrated monitoring procedures for assessing the processes triggered within the reservoir by a long term injection [1]. For a comprehensive characterization of the reservoir, its geological environment, and of the processes occurring due to the injection of CO_2, physical, chemical, and biological observations are carried out (Fig. 1). The geophysical methods provide the overall structure of the reservoir and the overlying strata, and they enable to observe the reaction of the reservoir and caprock to CO_2 propagation at locations

* Corresponding author. Tel.: +49-331-2881558; fax: +49-331-2881502.
E-mail address: slueth@gfz-potsdam.de.

doi:10.1016/j.egypro.2009.01.293

which are not accessible for direct observations. Additionally, chemical and biological investigations are carried out in order to perform a direct characterization of the interaction of the CO_2 storage with the surrounding rocks and fluids.

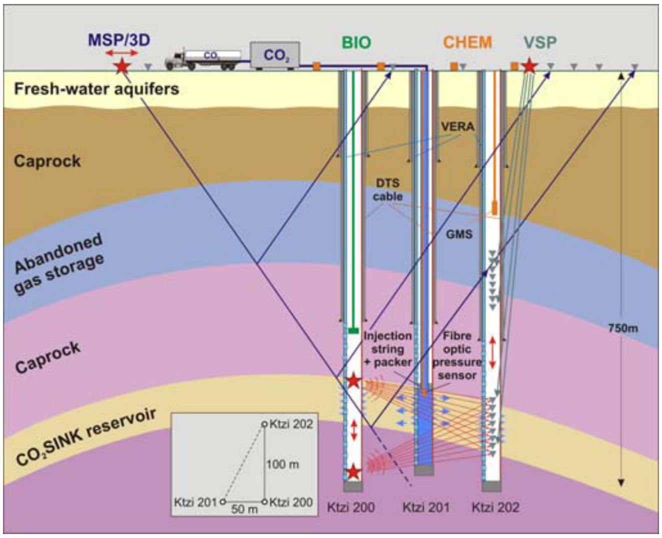


Fig. 1. Monitoring concept of the CO_2SINK project. Seismic monitoring: 3D, MSP (moving source profiling), VSP (vertical seismic profiling), crosshole tomography. Electrical monitoring: VERA (Vertical Electrical Resistivity Array). Temperature monitoring: DTS (Distributed Temperature Sensing). Pressure monitoring: fibre optic pressure sensor. Chemical Monitoring: Surface observations and GMS (Gas Membrane Sensor). Microbial investigations on fluid samples (BIO). The inset shows the relative positions of the boreholes Ktzi 200, Ktzi, 201, and Ktzi 202. Ktzi 201 is the injector, Ktzi 200 and Ktzi 202 are the observation boreholes. Figure by B. Schöbel (GFZ).

2. Seismic Monitoring

The seismic investigation program comprises baseline and repeat observations at different scales in time and space. 3D surface seismic baseline measurements, carried out in Fall 2005, provide the structural model around the location of the injection and monitoring boreholes [2]. The survey covers 12 km^2, illuminating every subsurface point by a fold of 25. The main objectives of the seismic survey were to verify earlier geologic interpretations of structure based on vintage 2D seismic and borehole data and to map, if possible, the reservoir pathways in which the CO_2 is injected, as well as providing a baseline for future seismic surveys and planning of drilling operations. The uppermost 1000 m are well imaged (Fig. 2) and show an anticlinal structure with an east-west striking central graben on its top. No faults are imaged near the drill sites. Remnant gas, cushion and residual gas, is present near the top of the anticline in the depth interval of about 250–400 m and has a clear seismic signature.

The 3D baseline survey was extended by VSP (vertical seismic profiling), MSP (moving source profiling) on 7 profiles, and crosshole tomographic measurements. 2D "star" measurements were carried out on the 7 MSP profiles in order to tie-in the down-hole surveys with the 3D baseline survey. These measurements provide enhanced resolution in time (faster and more cost effective than a full 3D survey) and space (higher source and receiver frequencies). Three crosshole measurements were performed, one baseline survey in May 2008, and two repeats in July and September 2008, respectively. The observation wells Ktzi 200 and Ktzi 202 were used as source and receiver holes, respectively. A third crosshole repeat is planned for a later stage in the project when a steady state situation has been reached in the reservoir between the two observation boreholes Ktzi 200 and Ktzi 202.

The interpretation of the time lapse crosshole seismic measurements is still work in progress. A preliminary evaluation of the results has shown that the time lapse effect of the CO_2 being injected in Ktzi 201 is not visible in the traveltimes of the direct compressional wave, indicating that to date, no significant change in the seismic velocities of the reservoir has occurred. A time lapse effect could be recognized on cross correlations of baseline and repeat data indicating that considering the full wave form of the recordings does have the potential to locate subtle changes in the seismic properties of the reservoir due to CO_2 injection.

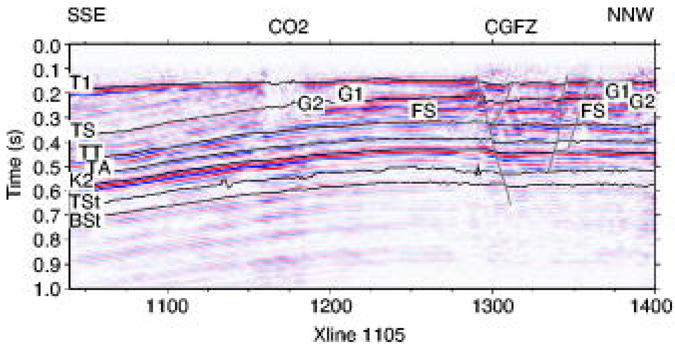


Fig. 2. Crossline 1105 of the 3D baseline data, crossing nearly over the top of Ketzin anticline. Mapped reflection horizons: T1 – near Base Tertiary, TS – near Top Sinemurian, TT – near Top Triassic, TA – near Top Arnstadt Formation, K2 – Top Weser Formation, TSt – near Top Stuttgart Formation, BSt – near Base Stuttgart Formation. CGFZ, G1, G2, and FS indicate the upper gas layer, the lower gas layer and the flat spot, respectively, corresponding to residual gas in the reservoir formerly used as a gas storage site. Depth in kilometres corresponds roughly to time in seconds.

3. Geoelectric Monitoring

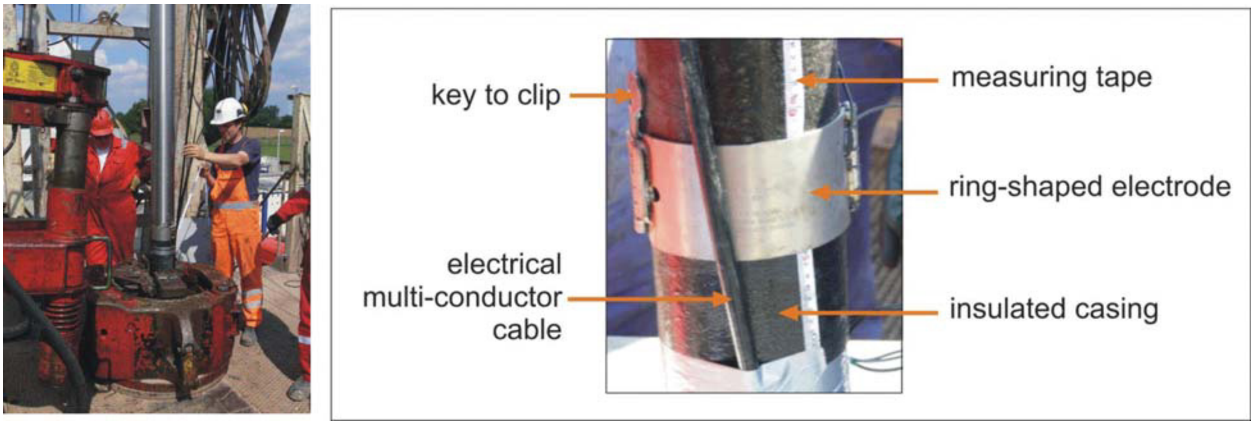
Geoelectric methods are well established for processes involving fluids and their transport mechanism. In particular, Electrical Resistivity Tomography (ERT) has been evaluated as suitable method for monitoring the subsurface fluid flow processes as tank leakages, water flood events, oil/water contact movements, and contaminant infiltrations [3] [4] [5]. Recent studies have shown the potential of ERT to detect the resistivity changes caused by CO_2 injection and migration in geological reservoirs [6] [7]. The electrical resistivity of the rock/brine system depends on properties as water saturation, permeability and porosity, which are simultaneously the most relevant parameters to describe the CO_2 plume propagation in the reservoir.

For the Ketzin test site, a Vertical Electrical Resistivity Array (VERA) was developed together with the Distributed Temperature Sensing (DTS) and the downhole pressure measurements as “smart-casing” technology for the CO2SINK wells (Fig. 1). The array consists of 45 permanent electrodes (15 in each well), placed on the electrically insulated casings of the wells in the 600 m to 750 m depth range with a spacing of 10 m. This layout has been designed according to numerical forward modeling assuming electrical properties of pre- and post-injection scenarios. The finally determined number of electrodes, their spacing along each well, and the horizontal-to-vertical ratio of the image plane for each well and for the whole triangular setup results in a suitable compromise between resolution of CO_2 migration features and cost.

In addition to the downhole measurement setup, surface to surface, and surface to downhole measurements are added in order to enlarge the area of observation between the three Ketzin wells to a hemispherical area (with a radius of about 1.5 km) around the wells. The combined measurements ensure the real CO_2-migration paths through the sandstone formation. Anisotropy effects in resistivity can be detected in the enlarged hemispherical area and directional inequalities in migration can be located.

The data acquisition system (Zonge Engineering and Research Organization, Inc., USA) consists mainly of a frequency programmable power supply, a multi-function receiver, two electrode multiplexers and a laptop as control panel.

The three multiconductor VERA-cables are directly connected with the multiplexer units, which allows switching from one electrode pair to another according so-called measurement schedules. During measurement, an electrical DC-signal is injected into a pair of two electrodes (user-defined), and the resulting potential difference is measured between other electrode pairs. The most common configurations use the dipole-dipole as well as the bipole-bipole measurement schemes. The time for one complete cross-hole cycle depends on the total number of electrodes, the measurement frequency and the repeating cycle of measurements. For the Ketzin wells with a total number of 45 electrodes, one complete cross-hole measurement cycle can be operated in about one hour.



,
Figure 4. Smart casing installation (left) and details of the VERA electrode design (right).

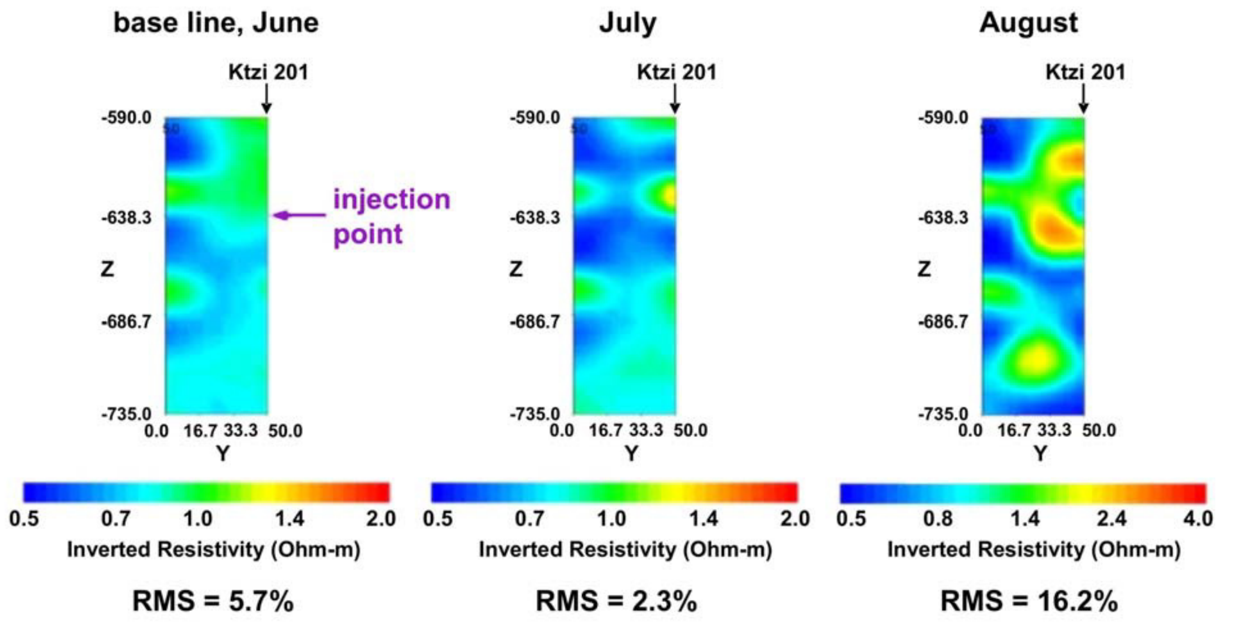


Fig. 5. Evaluation of 2D-slices as preliminary results of resistivity mapping of the reservoir in the near-borehole area. The inversion was carried out using the EarthImager3D software.

The raw data (voltage-to-current ratio) are converted to apparent resistivity and inverted to obtain 3D images of the true resistivity distribution in the reservoir, which reflects the extent of the CO2 plume. The resistivity data provide information about the saturation state of the reservoir independently of seismic methods.

From the start of CO2 injection in the end of June until today, the first phase of operation has been monitored and analyzed, as seen in Fig. 5. The cross-sections are extracted from the inverted 3D images using the EarthImager software (Advanced Geosciences Europe, S.L.). Higher resistivity values (presently up to factor 3 compared to other horizons) represent the intervals of the sandstone reservoir as preferred pathways of the CO2 propagation. The preliminary inversion results fit the expected reservoir behavior, and they are comparable to the results of the other monitoring techniques (gas composition and pressure measurements, temperature deviations, seismic surveys).

Further steps in the project are to determine the sensitivity of different electrode configuration types, to proceed time-lapse evaluation of a larger data set, and to perform a comprehensive error analysis of the field data in our inversion procedure.

4. Distributed Temperature Sensing

Both the injection well and the two observation wells are equipped with fiber-optic sensor cables for distributed temperature sensing (DTS). Using DTS technology, quasi-continuous temperature profiles can be measured on-line along the entire length of the wells with high temporal and spatial resolution (e.g. [8,9]).

At Ketzin, the DTS sensor cables are permanently installed behind the borehole casing. In contrast to conventional wireline logging, permanent installations behind casing offer the advantage of full access to the well during technical operations [10]. Apart from long-term temperature monitoring during the injection process, this also allowed for better control of the process of casing cementation [11], which is crucial to ensure the required sealing capability of the borehole completion for CO_2 storage wells. To enhance the thermal signal and improve the monitoring of brine and CO_2 transport, successive thermal perturbation experiments [12] are performed using an electrical heater cable installed adjacent to the DTS cables.

Intermittent measurements of the temperature profiles since the completion of the wells allowed to monitor the decay of the thermal disturbance caused by the drilling process and will now be used to determine the undisturbed formation temperatures. Since the start of CO_2 injection, the temperature distribution along the injection well and the two observation wells is monitored continuously. Figure DTS-1 contains temperature data extracted for particular depths of the wells for the initial two-month period after start of injection. Within this time the highest temperature changes of up to about +25 °C were observed close to the wellhead of the injection well. Temperature changes in the injection zone are in the order of 5 to 10 °C. In the two observation wells temperature changes of up to about 1.5 °C were measured within the reservoir section. A temperature increase of about 0.5 °C was observed at the reservoir level (upper filter screen) in Ktzi 200 prior to the time of breakthrough (b.t.) of CO_2 detected with the GMS sensor. The temperature anomalies detected with the DTS sensor cables allow to analyse flow processes within the wells and phenomena related to the spreading of CO_2, as well as to determine the reservoir sections which take up the CO_2 in the injection well.

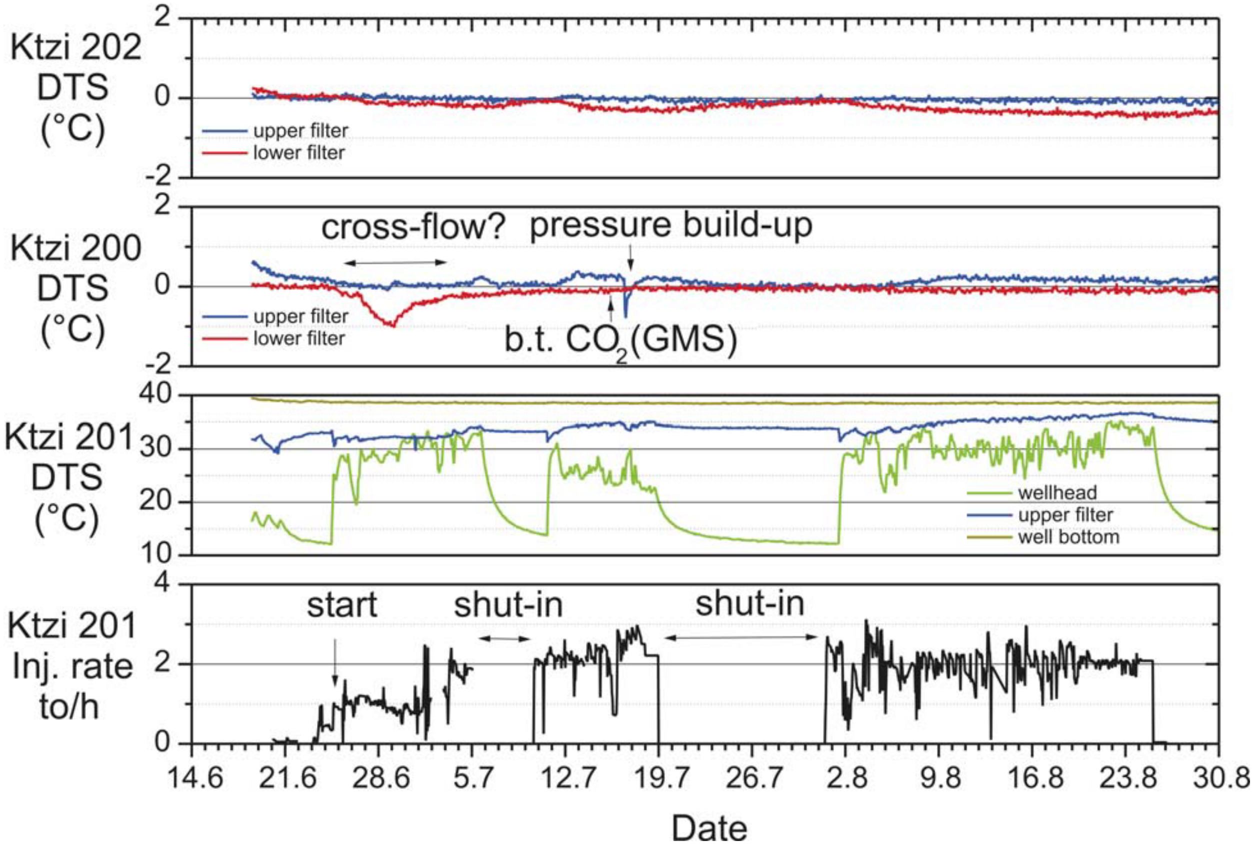


Figure 6. Injection rates and measured DTS temperatures in injection well (Ktzi 201) and temperature changes at the filter screens in the two observation wells (Ktzi 200 and Ktzi 202). Time of breakthrough (b.t.) of CO_2 detected with GMS sensor in Ktzi 200 is marked with an arrow.

5. Pressure Monitoring

A Fiber-Bragg-Grating (FBG) based pressure sensor has been installed in the well Ktzi201 at the end of the injection tubing string. The sensor assembly consists of the fiber optic gauge and transducer, the mandrel as carrier element, and the corresponding completion components. The system was designed by Weatherford International Ltd., and it contains no downhole electronics.

The sensor operates as single-point fiber optic pressure gauge and provides real-time measurements of wellbore pressure and temperature in the injection zone of the well.

The gauge is temperature compensated, and is designed to have a long life time at high temperatures. It utilizes two Bragg gratings, one primarily affected by system temperature and one affected by system temperature and pressure, packaged into a single all-glass sensing element. The transducer housing contains an oil-filled dual buffer tube assembly to prevent direct contact between the wellbore fluids and the sensing element and to serve as shock protection for the element. Maximum continuous operating conditions of the transducer are 150°C and 137 MPa.

The main application of the sensor is real-time monitoring of reservoir pressure during the injection process, and observation and control of the well in order to avoid critical situations during CO_2 injection operation. The data are needed for pressure transient analyses and reservoir characterization.

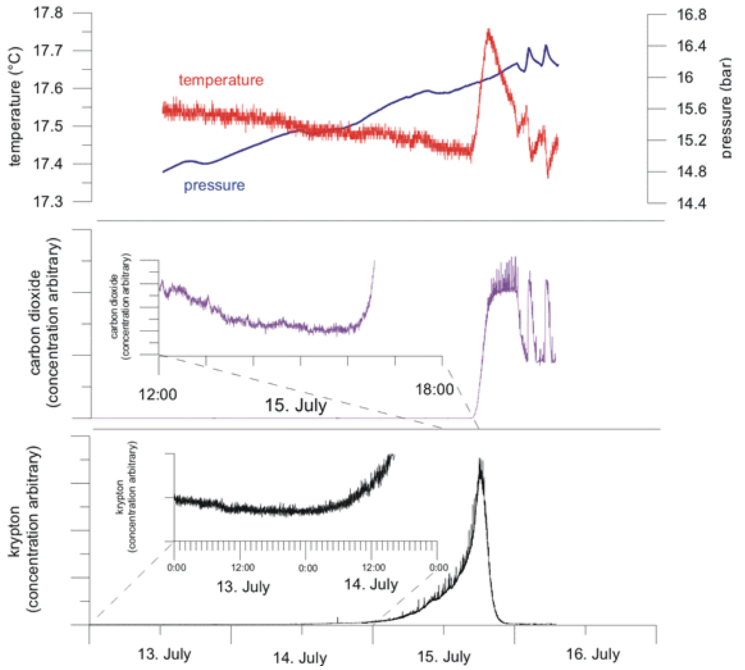


Fig. 7. Arrival of the injected krypton tracer gas and carbon dioxide in observation well Ktzi200/07 as well as pressure and temperature records.

6. Geochemical Monitoring

A new, innovative geochemical monitoring tool for the real time and in-situ determination of CO_2 and other gases in the observation bore holes at Ketzin was developed and applied. The method uses a phase separating silicone membrane, permeable for gases, in order to separate gases dissolved in borehole fluids, water and brines. Argon is used as a carrier gas to conduct the collected gases through capillaries to the surface. Here, the gas phase is analyzed in real-time with a portable mass spectrometer for all permanent gases. In addition, gas samples may be collected for more detailed investigations in the laboratory.

Downhole extraction and on-line determination of gases dissolved in brines using this gas membrane sensor technique was successful applied at the scientific CO_2 storage test site in Ketzin, Germany. Increasing reservoir gas concentrations of helium, hydrogen, methane and nitrogen during CO_2 injection were determined. The arrival of injected krypton tracer gas at the monitoring well was observed and changes in hydraulic pressure and temperature were measured (Figure 7). The breakthrough of CO_2 into the observation well, at 50m distance, was recorded after the injection of 531,5t CO_2 .

7. Microbial Monitoring

The main emphasis of the microbial monitoring is put onto locating, identifying and analysing the composition and activity of the microbial community, unravelling the origin and fate of dissolved organic matter (potential substrates and metabolites of microorganisms), and characterising microbial life in extreme habitats and its influence on creation and dissolution of minerals as well as their impact on the technical effectiveness of the CO_2 storage technique. In order to investigate processes in the deep biosphere rock cores and fluid samples were collected from the reservoir rock of the CO_2 storage side in Ketzin. The microbial community of the samples was investigated using DNA analyses with the PCR SSCP method (PCR–Single-Strand-Conformation Polymorphism-Based Genetic Profiles of Small-Subunit rRNA Genes). The first results of the fluid samples analyses revealed high diversity of the saline aquifer inhabitants. The deep biosphere community was dominated by the haloalkaliphilic fermentative bacteria (*Orenia, Halomonas, Halolactibacillus, Halobacteroides* and others) and extremophilic organisms (*Deinococcus* sp.), coinciding with reduced conditions, high salinity and pressure. Beside halophilic bacteria the sulfate reducing bacteria (*Desulfotomaculum salinum*) were found, which are known to be involved in corrosion processes. The reactions between the microorganisms and the minerals of both the reservoir rock and the cap rock may cause major changes in the structure and chemical composition of the rock formations, corrosion at the casing and the casing cement around the well. Analyses of microbial community composition and its changes provide information about the efficiency and reliability of the long-term CO_2 storage technique.

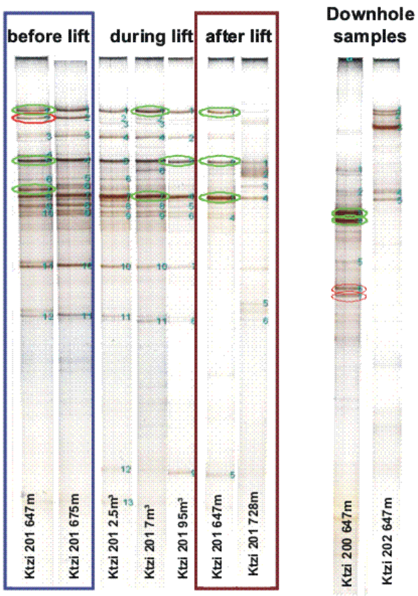


Fig. 8. The PCR-SSCP analyses of the fluid probes gained by N_2 lift and downhole sampling. Microbial community was dominated by fermentative bacteria (green) and sulphate reducing bacteria (red).

8. Conclusion and outlook

A comprehensive and interdisciplinary monitoring program is performed at the CO2 storage pilot project in Ketzin (Germany). This program provides the data base for an integrated reservoir characterization and observation of physical, chemical, and biological processes triggered by the long term storage of carbon dioxide in a saline aquifer. An integrative interpretation of the monitoring data will be performed in the near future including a multiparameter inversion of the geophysical monitoring techniques and considering innovative modeling procedures accounting for the coupling of thermal, hydrological and chemical processes.

Acknowledgements

The CO_2SINK project receives its funding from the European Commission (Sixth Framework Program, FP6) and two German ministries, the Federal Ministry of Economics and Technology (CO_2 Reduction Technologies for Fossil Fueled Power Plants, COORETEC Program) and the Federal Ministry of Education and Research (GEOTECHNOLOGIES Program).

Special thanks are extended to Dr. William D. Daily from the Lawrence Livermore National Laboratory for his helpful comments and fruitful discussions in the phase of planning the VERA system.

References

[1] Schilling, F., G. Borm, H. Würdemann, F. Möller, M. Kühn, A. Liebscher, and CO_2SINK Group (2008), Status Report on the First European on-shore CO_2 Storage Site at Ketzin (Germany), In Proceedings of the 9th International Conference on Greenhouse Gas Control Technologies, November 16-20, Washington, D.C.

[2] C. Juhlin, R. Giese, K. Zinck-Jørgensen, C. Cosma, H. Kazemeini, N. Juhojuntti, S. Lüth, B. Norden, and A. Förster, 3D baseline seismics at Ketzin, Germany: the CO2SINK project. Geophysics 72 (2007) 5, B121-B132.

[3] L. Slater, A.M. Binley, W. Daily, R. Johnson, Cross-hole electrical imaging of a controlled saline tracer Injection, *Journal of Applied Geophysics*, 44 (2000) 85–102.

[4] R. van Kleef, R. Hakvoort, V. Bushan, S. Al-Khodhori, W. Boom, C. de Bruin, K. Babour, C. Chouzenoux, J.P. Delhomme, Y. Manin, D. Pohl, E. Rioufol, M. Charara, R. Harb, Water Flood Monitoring in an Oman Carbonate Reservoir Using a Downhole Permanent Electrode Array, SPE 68078.

[5] I.D. Bryant, M.-Y. Chen, B. Raghuraman, I. Raw, J.-P. Delhomme, C. Chouzenoux, D. Pohl, Y. Manin, E. Rioufol, G. Oddie, D. Swager, J. Smith, An application of cemented resistivity arrays to monitor waterflooding of the Mansfield sandstone, Indiana, USA, *SPE Reservoir Evaluation and Engineering,* **5**, No. 6, (2002), 447–454.

[6] A. L. Ramirez, R. L. Newmark, W. D. Daily, Monitoring Carbon Dioxide Floods Using Electrical Resistance Tomography (ERT): Sensitivity Studies, *Journal of Environmental and Engineering Geophysics*, Volume 8, Issue 3 (2003),187–208.

[7] N.B. Christensen D. Sherlock K. Dodds, Monitoring CO_2 injection with cross-hole electrical resistivity tomography, *Exploration Geophysics* (2006) **37**, 44-49.

[8] Hurtig, E., J. Schrötter, S. Grosswig, K. Kühn, B. Harjes, W. Wieferig, and R. P. Orrell (1993), Borehole temperature measurements using distributed fibre optic sensing, *Scientific Drilling*, *3* (6), 283-286.

[9] Förster, A., J. Schrötter, D. F. Merriam, and D. D. Blackwell (1997), Application of optical-fiber temperature logging; an example in a sedimentary environment, *Geophysics*, *62* (4), 1107-1113.

[10] Henninges, J., G. Zimmermann, G. Büttner, J. Schrötter, K. Erbas, and E. Huenges (2005), Wireline distributed temperature measurements and permanent installations behind casing, in *Proceedings of the World Geothermal Congress 2005, Antalya, Turkey [CD-ROM]*, edited by R. Horne and E. Okandan, paper 1021, International Geothermal Association, Reykjavik, Iceland.

[11] Prevedel, B., L. Wohlgemuth, B. Legarth, J. Henninges, H. Schütt, C. Schmidt-Hattenberger, B. Norden, A. Förster, and S. Hurter (2008), The CO2SINK boreholes for geological CO_2-storage testing, paper presented at 9th International Conference on Greenhouse Gas Control Technologies, Washington, November 16-20.

[12] Freifeld, B. M., T. Daley, S. Hovorka, J. Henninges, J. Underschultz, and S. Sharma (2008), Recent advances in well-based monitoring of geologic carbon sequestration, paper presented at 9th International Conference on Greenhouse Gas Control Technologies, Washington, November 16-20.